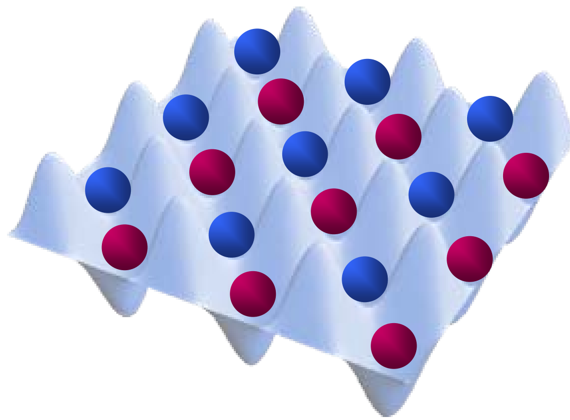
Optical Lattice Emulator

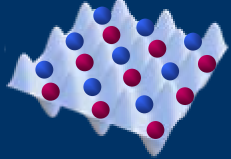


Proposer's Workshop, 12/5/2006

Jay Lowell

Program Manager

DARPA DSO

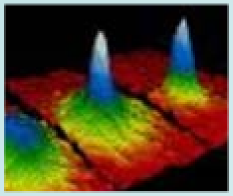


The OLE Tool – a means for emulating computationally intractable systems

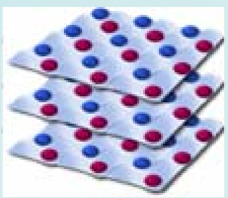
OLE

Recent Scientific Breakthroughs + **Innovative Experimental Controls**

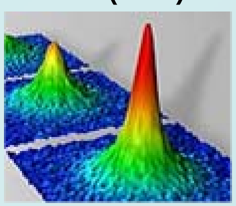
Bose-Einstein Condensate (1995)



Optical Lattices (1997)



Degenerate Fermi Gas (1999)



1. System initialization
- Set Temperature
- Specify Filling Factor
- Engineer the Interaction…

2. Emulation control
- Tunneling
- Interaction
- Atom Density…

3. Final state characterization
- Phases of Strongly Correlated System
- Order Parameters…

The OLE tool will build on cutting edge science to attack currently intractable material science problems.

New Phases of Matter
- Supersolids
- Spin liquids

Verify Physical Models for Technologically Important Materials
- High-T_c superconductivity
- Quantum magnetism

OLE BAA: Program Objective and Teams

- **Objective:** Develop a tool based on cold atoms in optical lattices that will enable emulation of computationally intractable condensed matter systems or materials for which we have no verifiable theoretical solution or experimental realization.

- It is expected that each research effort will consist of an ***interdisciplinary team*** capable of developing the following:
  1. Techniques for producing ultra-cold degenerate gases.
  2. Techniques for producing and manipulating optical lattices.
  3. Techniques for engineering specific Hamiltonians relevant to strongly-correlated condensed matter systems.
  4. Techniques for characterizing cold atoms, ions, or molecules in periodic traps.
  5. Theoretical and computational techniques that support the development of methods for measurement of system properties, verification of experimental parameters, and validation of the fidelity of the entire optical-lattice-based emulator.

- To realize the program vision and meet the Phase I milestones, each research effort requires performers with expertise in all of the following areas:
  1. Experimental production of ultra-cold degenerate quantum gases (BEC and DFG). In particular, expertise in the rapid production of the degenerate gases, precision experimental control, and novel measurement techniques will be necessary.
  2. Experimental production, control, and characterization of optical lattices.
  3. Theoretical atomic physics.
  4. Theoretical condensed matter physics, especially computational efforts to predict phase properties of strongly-correlated many-body Hamiltonians.

OLE BAA: Phase I and Phase II

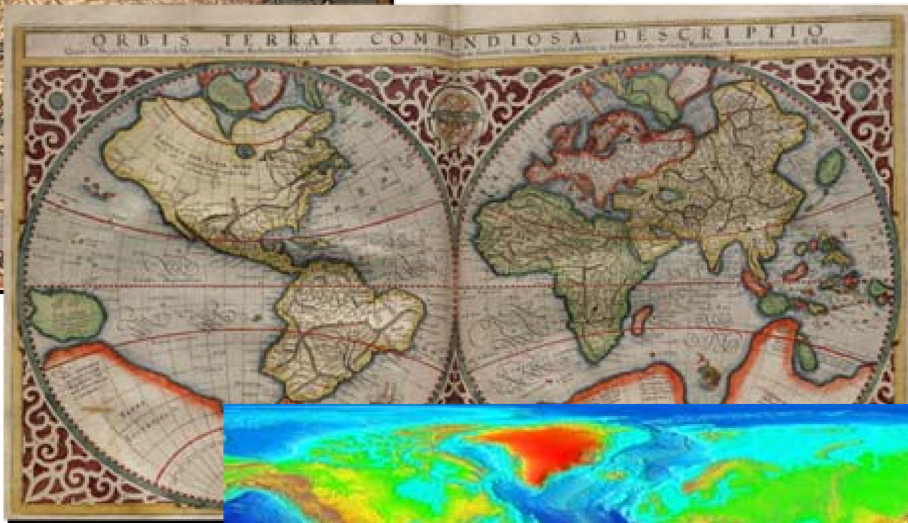
- **Phase I Goal** (duration: 24 months or less)
  - Validate the underlying techniques by ultimately producing a phase diagram depicting distinct thermodynamic and/or quantum-mechanical phases for a benchmark Hamiltonian as a function of at least two relevant variables.
- **Phase I Milestones**
  1. Design, build, and utilize an Optical Lattice Emulator to achieve the Phase I goal. This experimental characterization ("emulation") should be completed in less than 12 hours, and must be repeatable.
  2. Verify OLE output by theoretical or computational means for the physically realized Hamiltonian. The comparison between OLE output and the theoretical or computational verification should be done for an identical number of plotted points in the phase diagram, and should show identical behavior in each phase identified. The location of the phase transition(s) produced by the OLE output should be verified to be accurate to better than 90%. Example
- **Phase II Goal** (duration: expected between 24-36 months)
  - Extend the OLE tool to the verification of Hamiltonian models that have novel phases, such as high-T_c superconductivity, spin liquids, or supersolids.

Development of robust tools for mapping

15th century depiction of the Ptolemy world map, reconstituted from Ptolemy's Geographia (circa 150)

The Waldseemüller map (1507)

Mercator world map (1595)

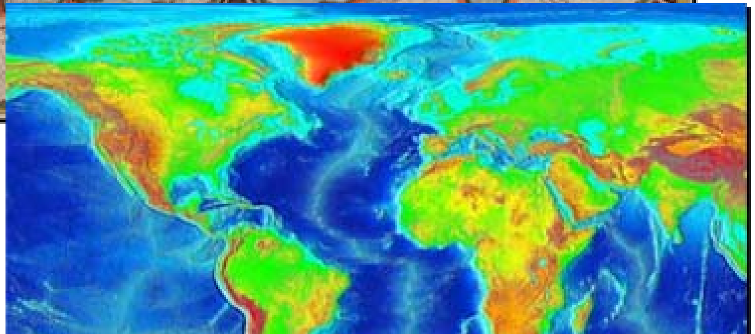


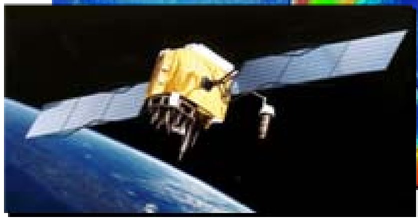
Astrolabe (>8th century)

Mariner's compass (>1300)

Sextant (>18th century)

Marine clock (>1750)





Satellites (>1960)

OLE BAA: Proposal Submission

- **Proposal Deadline**: January 12, 2007, no later than 4:00 pm ET.

- **Two volumes**: Technical and Cost.
- Required sections in the Technical Volume:

1. Technical Approach
   a. Methods for producing optical lattices with geometry relevant to the chosen Hamiltonian.
   b. Technique for producing degenerate quantum gases and loading them into the optical lattices with control appropriate for the chosen Hamiltonian.
   c. Techniques for engineering the chosen Hamiltonian in the Optical Lattice Emulator, including control if interactions, atom distribution within the lattice, temperature, etc.
   d. Techniques for measuring and characterizing the engineered Hamiltonian in the Optical Lattice Emulator.
   e. A table showing the time required to produce the experimentally generated phase space diagram. This should address a time budget for all of the stages outlined above, clearly state any assumptions, and an estimate for the impact measurement signal to noise has on total emulation time.
2. Research Team: Clearly define the expertise of the individual team members and how their expertise relates to the research areas defined in the technical approach.

OLE BAA: Proposal/Technical Volume

3. Management Approach: Define a single Principal Investigator who will coordinate the team and be responsible for demonstrating the Go/No-Go project milestones listed below.
4. Phase I milestones:
   a. End of Phase I (Go/No-Go) milestones: The Go/No-Go milestones must include those outlined above for the Phase I program, and must be clearly and explicitly stated.
   b. Interim Phase I progress assessments: A list of smaller project accomplishments that must occur to meet the Go/No-Go milestone should be listed. These should be time-ordered (to the extent possible), and a lead researcher must be identified as responsible for that accomplishment.
5. Phase II Phenomena Demonstrations: Discuss a plan for extending the Phase I OLE tool beyond the validation by benchmark Hamiltonian. In particular:
   a. Outline the particular phase behavior(s) that will serve as the principle OLE tool demonstration(s), and how this (each) demonstration might be used to guide a follow-on experimental material development project.
   b. Discuss the means for verifying measurements made in the OLE tool for each of the above phase behaviors.
   c. Each OLE phase investigation should form its own task, and must be broken out separately in the Cost Volume. Note we are not asking for the proposal to actually explore material designs, but rather to provide a realizable approach for using their tool to do so.

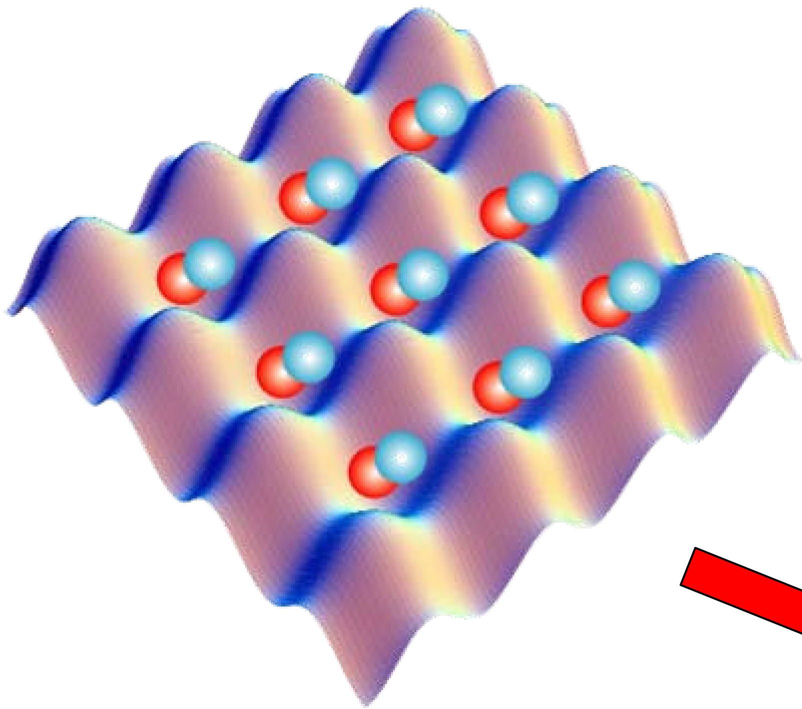
Ingredients for a Successful Proposal

- Each member of the team, and every project within the team effort, should be focused on a single common goal. [2, 3, 4, 5c]
  - Each member should make an integral contribution to the final demonstration.

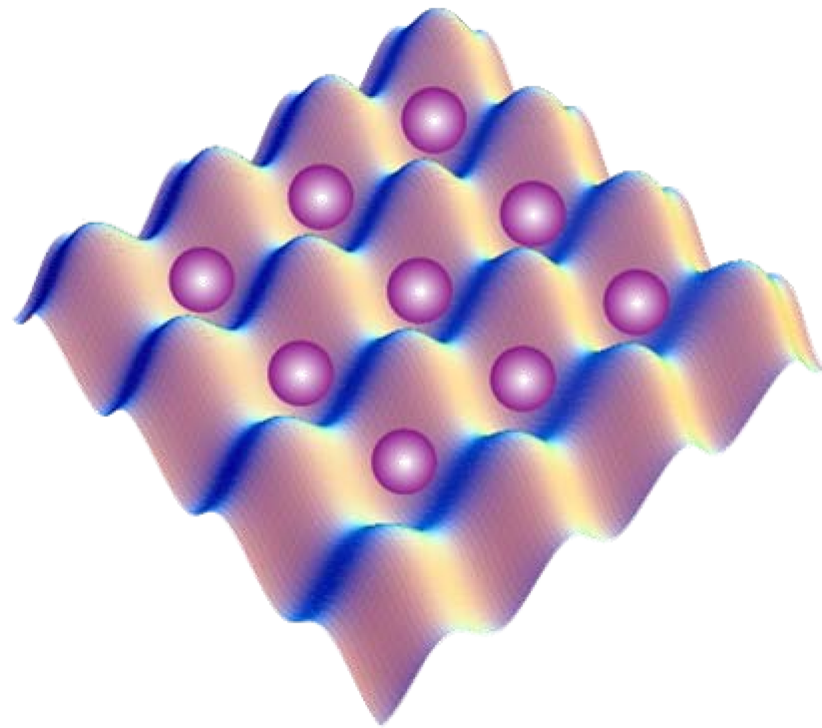
- The choice of the benchmark problem for Phase I must be justified clearly. [1, 4a, 4b, 5a, 5b]
  - The relevance of the benchmark problem to the Phase II goal must be clearly described in terms of relevant experimental and/or theoretical parameters (e.g., similar interactions and/or lattice filling/loading).
    - Characterize accurately what aspects of the Phase II goal are not addressed or resolved in the benchmark problem (e.g., your targeted Hamiltonian includes interactions not included in the benchmark Hamiltonian).
    - How will these aspects be addressed in Phase I (e.g. Experimental and/or theoretical solutions)
  - Reliable theoretical (analytic and/or numeric) solution must exist for the chosen benchmark problem.

- For a chosen lattice-based model, state clearly the overarching science or technological problem that you are attempting to solve and why it is important. [5a]

Toy Example – Blue-Red Hamiltonian

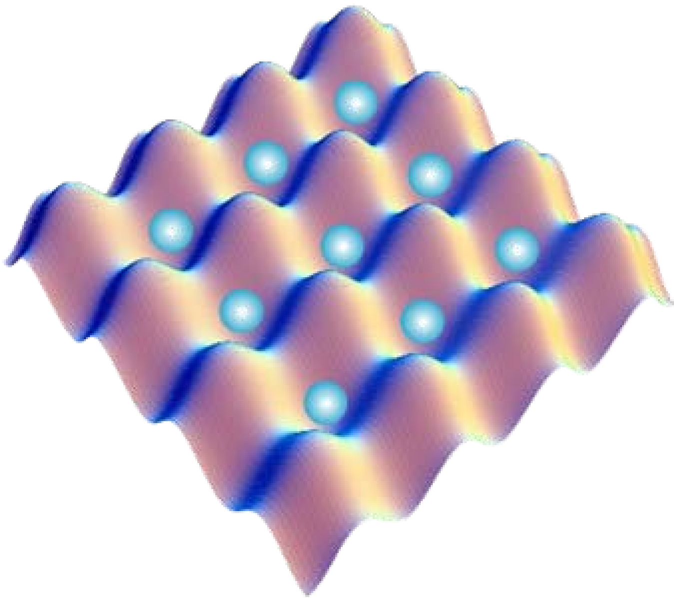


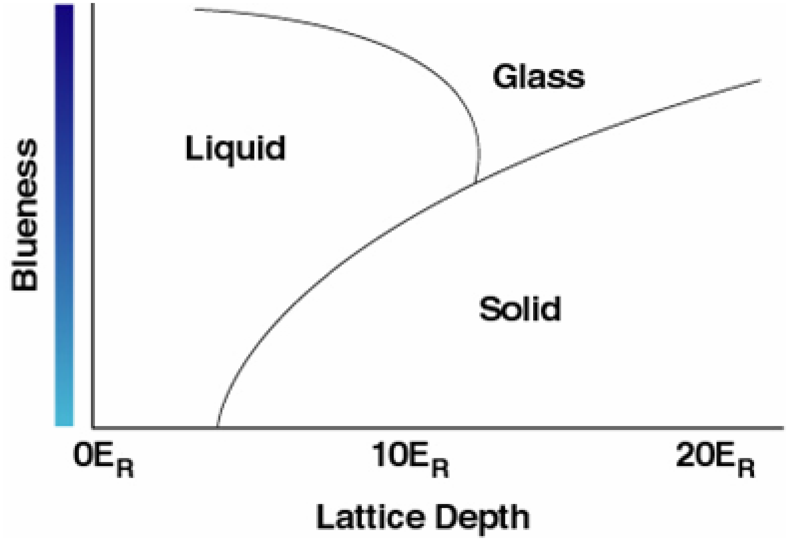
- The Purple phase has very important implications in condensed matter physics.
- Unfortunately, a direct signature is difficult to detect in solids due to additional Yellow interactions.



- Theorists predict that Bluon-Redicle mixtures can undergo a transition to a Purple phase. The necessary conditions are:
  - Unity occupation per site of each species.
  - Weak Blue-Red Interactions

Toy Example – Blue-Red Hamiltonian
Phase I Benchmark Problem – Blue Hamiltonian





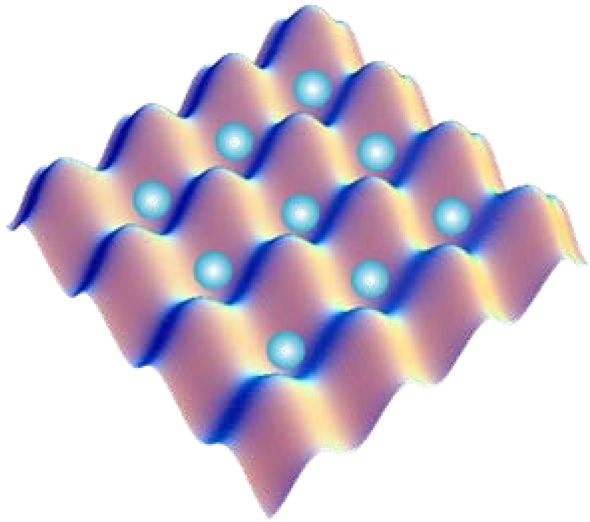
- Bluons in a periodic lattice have a readily solvable phase diagram (shown above).
- Exploring the Blue Hamiltonian is the most logical step towards solving the Blue-Red Hamiltonian.
- Additional pieces to the Blue-Red puzzle (blue-red interactions) can be studied in bulk.

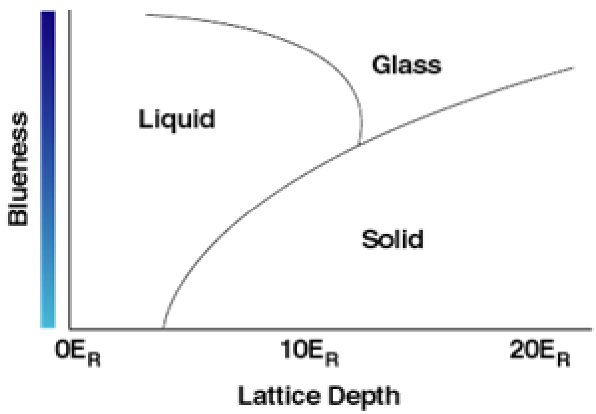
Benchmark Hamiltonian

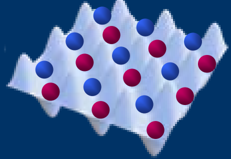
- 12 hours to map out Blue phase diagram at 90% confidence level.

Model-Specific Milestones (interim or otherwise)

- Production
  - Simultaneous production of cold bluons and redicles in bulk.
- Interactions
  - Individual control over blueness and redness.
  - Cross interactions between bluons and redicles in bulk.
- Loading
  - Lattice can be loaded with unity occupation (either species).
  - Lattice is capable of holding both species at suitable depth.
- Theory
  - Determination of a realistic parameter space for Purple phase search.
  - Detection scheme for observing Purple phases.
  - Lattice loading scheme for dual occupation.

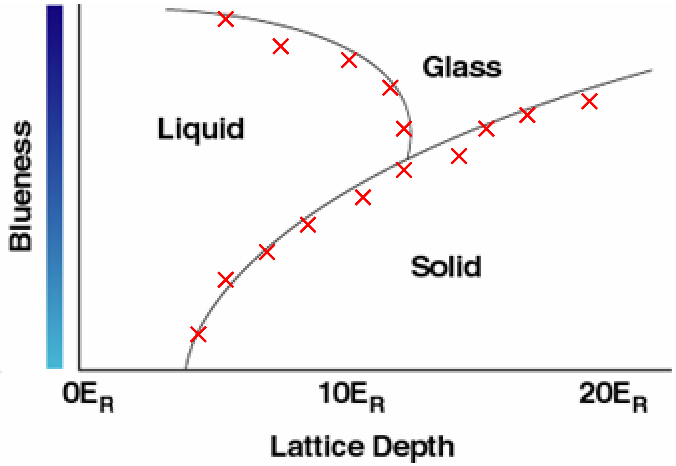






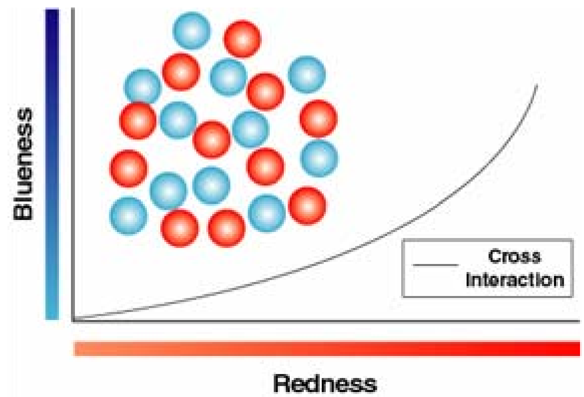
Toy Example – Blue-Red Hamiltonian Phase I Completion

Benchmark Problem

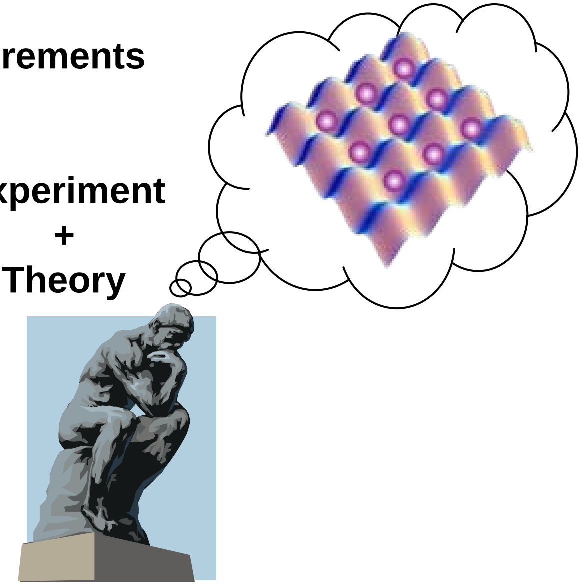


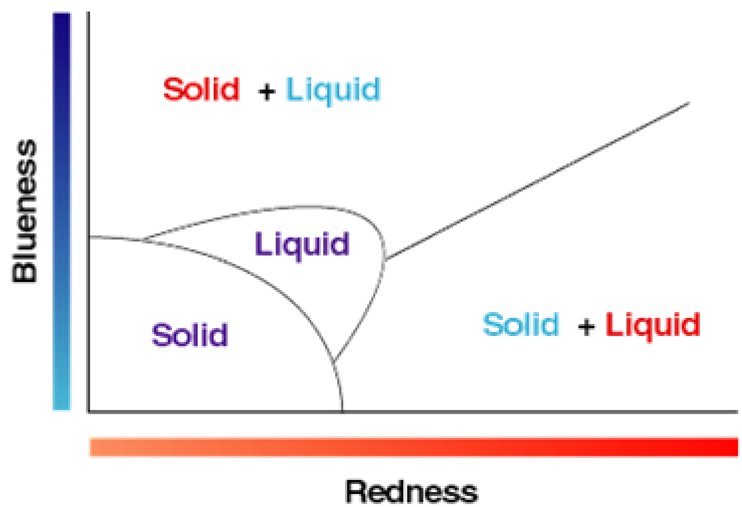
+

Model Specific Requirements



Experiment
+
Theory





Phase II

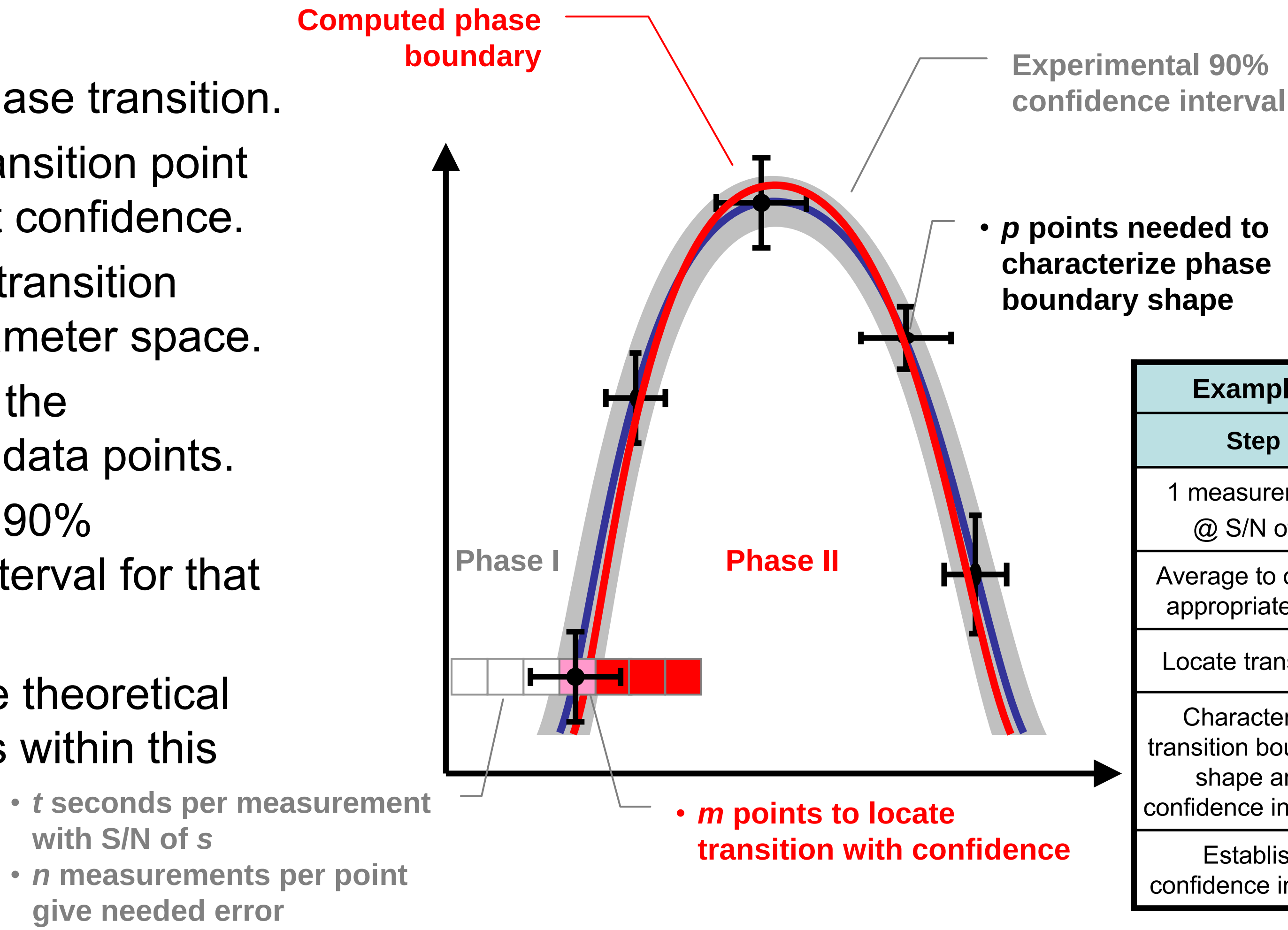
- With most of the necessary pieces to the puzzle in place the experiment proceeds to Phase II.

Verification of Phase Diagram
Calculation of Emulator Output Time

Back

An example of mapping phase diagram to 90% confidence level:

1. Search for phase transition.
2. Locate the transition point with sufficient confidence.
3. Locate other transition points in parameter space.
4. Fit a curve to the experimental data points.
5. Establish the 90% confidence interval for that curve.
6. Verify that the theoretical prediction lies within this interval.



Example Time Budget	
Step	Time (s)
1 measurement @ S/N of *s*	t
Average to obtain appropriate S/N	$n \cdot t$
Locate transition	$m \cdot (n \cdot t)$
Characterize transition boundary shape and confidence intervals	$p \cdot [m \cdot (n \cdot t)]$
Establish confidence interval	$q \cdot [p \cdot m \cdot n \cdot t]$

For $t \approx 9s$, reasonable assumptions give total output times just under 12 hours

Any Questions?